Small Polarons in a Dilute Bose-Einstein Condensate

Fernando M. Cucchietti and Eddy Timmermans, T-4

Since the 1995 realization of dilute gas Bose-Einstein condensation [1], the area and technology of cold atom physics grew at an astonishing pace. Following Bose's derivation of the spectral density of thermal light from the statistics of indistinguishable "Bose" particles, Einstein predicted in 1924 that a significant fraction of such particles, if their number is conserved, occupy (or "condense" into) the same single particle state at sufficiently low temperatures. The current cold atom technology provides an impressive ability to study and manipulate this laser-like state of matter. This system, the Bose-Einstein condensate (BEC) has served as a paradigm of superfluidity.

The observation of a superfluid's response after the insertion of "foreign" — distinguishable — particles has been a successful method to study their microscopic structure. In cold atom physics, this strategy led to the demonstration of dissipationless flow in dilute BECs [2]. In these experiments, a number of impurities were created in the BEC with controllable momentum. The sudden suppression of incoherent scattering of sufficiently slow impurities by the BEC illustrated the superfluid ability of sustaining dissipationless flow.

Quantum mechanically, however, the probe necessarily affects the measured system. Recently, we found [3] that even when the change in the condensate due to the presence of the impurity is almost negligible, it can be enough to "back-react" on the impurity and modify its nature drastically. In particular, we show that there exists a regime where the impurities in the condensate can self-localize.

The process is similar to the formation of a small polaron in a solid. When an impurity interacts with the particles of a homogeneous condensate, it pulls (or repels, depending on the sign of the interaction) some bosons so that a small bump in the condensate density appears. The variation of the BEC-density provides a local minimum of the effective potential experienced by the impurity. If the impurity-boson interaction is sufficiently strong, the potential minimum is deep enough to pay for the kinetic energy cost of localizing the impurity atom, thereby trapping it near the density variation originated by the impurity's localization.

Fueled by a host of scientific and technological prospects, the localization of particles within a BEC has been pursued for the past several years. Our proposal — inducing self-localization

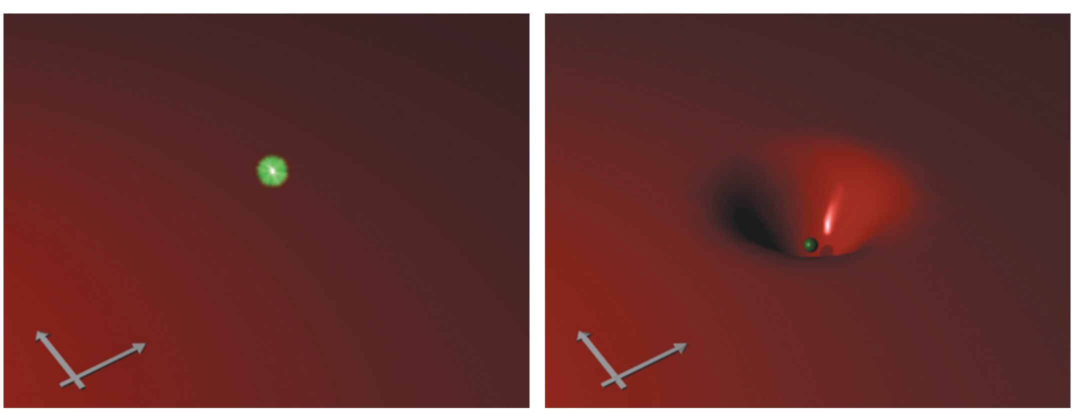

Fig. 1. ***Informal representation of the formation of the polaron. On the left, an extended wavefunction for the impurity (green) interacts with the condensate particles (red). On the right, the interaction with the impurity distorts the condensate density creating a local minimum for the impurity's effective potential. If the interaction is strong enough, the impurity will self-localize.***

by increasing the impurity-boson interaction — can achieve this elusive goal and provide the flexibility and versatility necessary to create quantum-dot like single-particle devices, test the Unruh effect, provide a mean to isolate and transport quantum bits in cold atom quantum information experiments and realize other fascinating applications.

Summing up, our work opens up an avenue of research inside the field of cold atom gases. The regime of formation of the polarons is well within state-of-the-art experimental technology. We expect that the intriguing prospects will entice experimental groups to test our prediction, thereby posing new theoretical and experimental challenges. The small BEC-polaron would then join the cold atom toolbox, both as a technique and as an object for fundamental physics studies.

For more information contact Fernando M. Cucchietti at fercook@lanl.gov.

[1] M.H. Anderson, et al., Science 269, 198 (1995); K.B. Davis, *Phys. Rev. Lett.* **75**, 3969 (1995).
[2] A.P. Chikkatur, et al., *Phys. Rev. Lett.* **85**, 483 (2000)
[3] F.M. Cucchietti and E. Timmermans, "Small polarons from neutral impurity atoms in a dilute Bose-Einstein condensate," cond-mat/061228.

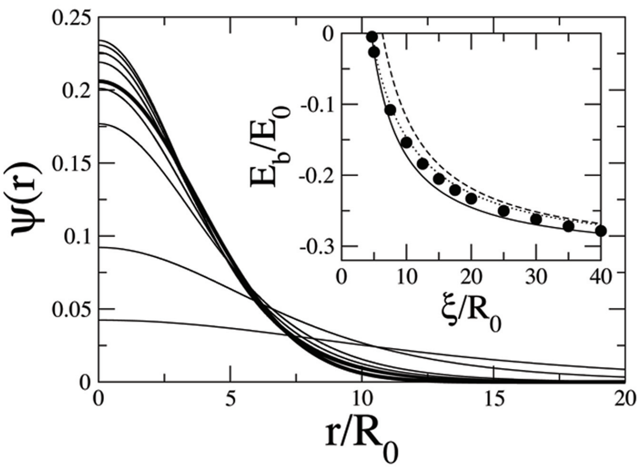

Fig. 2. ***Radial wavefunction of the impurity obtained numerically for increasing values of the healing length of the condensate ξ (from bottom to top). In bold line, the initial Gaussian ansatz. In the inset, the energy of the ground wavefunction vs ξ (dots). In dotted line, a variational calculation. The analytical expansion for large ξ is in dashed line, and the best fit to the data $E_b/E_0 \approx -1/\pi + 1.5\, R_0/\xi$ in solid line. [All lengths and energies are in units of the Bohr radius R_0 and Rydberg energy E_0 (respectively) of the effective Coulomb potential suffered by the impurity at infinite healing length.]***